Retreat pattern and dynamics of glaciers and ice sheets: reconstructions based on meltwater features

Martin Margold
ABSTRACT

Glaciers and ice sheets covered extensive areas in the Northern Hemisphere during the last glacial period. Subsequently to the Last Glacial Maximum (LGM), they retreated rapidly and, except for Greenland and some other ice caps and glaciers, they vanished after the last glacial termination. This thesis examines the dynamics of deglacial environments by analysing the glacial geomorphological record with focus on the landforms created by glacial meltwater. The aims are (i) to evaluate the data available for mapping glacial meltwater features at the regional scale, and (ii) to demonstrate the potential of such features for regional ice retreat reconstructions in high-relief landscapes. Meltwater landforms such as ice-marginal meltwater channels, eskers, deltas and fossil glacial lake shorelines are used to infer former ice surface slope directions and successive positions of retreating ice margins.

Evaluated high-resolution satellite imagery and digital elevation models reveal their potential to replace aerial photographs as the primary data for regional mapping surveys including the glacial meltwater system. Following a methods study, reconstructions of the deglacial dynamics are carried out for the area of central Transbaikalia, Siberia, Russia, and for the Cordilleran Ice Sheet (CIS) in central British Columbia, Canada, using regional geomorphological mapping surveys.

Mapped glacial landforms in central Transbaikalia show evidence of a significant glaciation that possibly extended beyond the high mountain areas. Large glacial lakes were formed as advancing glaciers blocked rivers, and of these, Glacial Lake Vitim was the most prominent. Traces of intensive fluvial erosion in the postulated area of glacial damming possibly indicate a high-magnitude outburst flood from this glacial lake.

Deglacial dynamics of the CIS reconstructed from the meltwater landform record reveals that the configuration of its southern sector changed after the local LGM. The ice divide shifted to the Coast Mountains in north-central British Columbia and the eastern margin retreated from the Rocky Mountains. Similarly to the situation in central British Columbia, the Liard Lobe in the northeastern sector of the CIS also retreated in a western direction towards the ice divide. The role of eastern accumulation areas appears to have diminished after the LGM and little evidence is available for their survival during the later stages of deglaciation.

The results presented in this thesis demonstrate the potential to reconstruct ice retreat patterns and deglacial dynamics at regional scales by interpretation of the meltwater landform record from shrinking glaciers and ice sheets.
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This thesis consists of a summary and six papers:

**Paper I**

**Paper II**

**Paper III**

**Paper IV**

**Paper V**
Margold, M., Jansson, K.N., Kleman, J., Stroeven, A.P., Clague, J.J. (in review): Late-glacial retreat pattern of the Cordilleran Ice Sheet in central British Columbia reconstructed from glacial meltwater landforms. *Quaternary Science Reviews*. [Supplementary material on enclosed CD]

**Paper VI**
Margold, M., Jansson, K.N., Kleman, J., Stroeven, A.P. (manuscript): Late-glacial ice dynamics of the Cordilleran Ice Sheet in northern British Columbia and southern Yukon Territory: retreat pattern of the Liard Lobe reconstructed from the glacial landform record.

**Co-authorship**

Paper I: I conducted the mapping, carried out the field-checking and wrote the manuscript. Krister Jansson supervised the mapping, contributed to the writing and participated in the field-checking. Arjen Stroeven helped with the final manuscript preparation.

Paper II: I conducted the mapping and wrote the manuscript; Krister Jansson supervised the mapping and contributed to the writing. Arjen Stroeven helped with the final manuscript preparation.

Paper III: Johan Kleman suggested the initial approach. I conducted the mapping, carried out the field-checking and wrote the manuscript. Krister Jansson and Arjen Stroeven contributed to the manuscript preparation; Johan Kleman reviewed the final draft of the manuscript.

Paper IV: I carried out the GIS analysis and the interpretations and wrote the manuscript. John Jansen, Krister Jansson and Arjen Stroeven contributed to the interpretations and writing.

Paper V: I did the data analysis and interpretation and wrote the manuscript. John Clague, Arjen Stroeven, Krister Jansson and Johan Kleman contributed to the writing.

Paper VI: I did the data analysis and interpretation and wrote the manuscript. Krister Jansson, Arjen Stroeven and Johan Kleman contributed to the writing.
1. Introduction

Ice sheets advanced and retreated over large parts of the Northern Hemisphere, and to a lesser extent in the high latitudes and altitudes of the Southern Hemisphere, during the Pleistocene (Mercer, 1976; Barendregt and Irving, 1998; Svendsen et al., 2004). The impact these ice sheets exerted on the landscape varied in space and over time (Kleman et al., 2008; Lambeck et al., 2010), and in some regions ice sheets were the primary geomorphological agents shaping modern relief (Sugden, 1974; Kleman et al., 2008). At the same time, mountain glaciation has substantially modified the appearance of most mountain ranges, and possibly also played an active role in their rates of uplift (Molnar and England, 1990; Champagnac et al., 2007; Shuster et al., 2011). The presence and dynamics of glaciers and ice sheets and the concurrent climate fluctuations of the Quaternary have directly influenced the evolution of modern humans who settled the world during the middle and late Pleistocene (Dolukhanov, 1997; Hewitt, 2000; Gamble et al., 2004). The observed warming of recent decades (IPCC, 2007) directs an attention to the behaviour of the Greenland and Antarctic ice sheets (Oppenheimer, 1998; Overpeck et al., 2006) because the melting of these ice sheets would cause a widespread sea-level rise into densely populated coastal areas (Dowdeswell, 2006; Bamber et al., 2009). This all motivates an interest in past glacial environments and efforts to reconstruct the evolution and dynamics of the large ephemeral ice sheets (e.g., Svendsen et al., 2004; Kleman et al., 2010) and such short-lived catastrophic events related to former glaciation that had the potential to change climate on regional or global scales (e.g., Broecker, 2006; Murton et al., 2010).

The most dramatic periods of the Quaternary were the terminations, times of rapid ice sheet retreat and meltwater release to the oceans in a rapidly ameliorating climate (Petit et al., 1999; Denton et al., 2010). These periods of climate warming and ice sheets retreat were interrupted by shorter periods when climate deteriorated abruptly and possibly switched back to full glacial conditions (Broecker et al., 2010; Denton et al., 2010). The period that offers the best insight into the environmental response to this dramatic and extensive change in climate, particularly in the Northern Hemisphere, is the last glacial termination (Rasmussen et al., 2006; Denton et al., 2010). During the deglaciation, a profuse amount of meltwater was produced by the decaying ice sheets. Part of the meltwater drained directly to the oceans causing sea levels to rise rapidly (Fairbanks, 1989) which, in turn, contributed to enhanced retreat of ocean-terminating ice margins (e.g., Booth et al., 2003). Meltwater was also stored in glacial lakes wherever retreating ice margins blocked natural drainage routes (Leverington et al., 2000, 2002; Jakobsson et al., 2007). Rapid discharges from glacial lakes are suggested to have caused major climate deteriorations. This is because the thermohaline circulation, redistributing energy on earth, was disrupted by such influx of cool freshwater into the North Atlantic and Arctic oceans (Barber et al., 1999, Teller et al., 2002; Tarasov and Peltier, 2005). At the same time, humans were closely trailing the retreating ice margins and settled recently deglaciated areas (Mithen, 2003). Of particular interest is the peopling of North America from the north after their passage from Asia across the emerged Bering Strait land bridge (Elias et al., 1996; Dixon, 2001). A long-lasting debate concerns possible dispersal routes following their entry in North America, which might have lead them through an ice free corridor between the retreating eastern Cordilleran and western Laurentide ice sheet margins or along the Canadian Pacific coast (Dixon, 2001; Mandryk et al., 2001; Waguespack, 2007). A knowledge of ice flow history and ice sheet dynamics has also a more utilitarian use as it allows for the tracing of important minerals of economic value back to their source areas (Levson et al., 2001). Furthermore, understanding former ice sheets is important as a component of the climate system (Oerlemans, 1991) and results of paleoglaciological reconstructions are used as constraints for numerical ice sheet models and global climate models (Golledge et al., 2008, Stokes and Tarasov, 2010; Heyman et al., 2011).

In this thesis, I examine the merits of using glacial meltwater landforms in paleoglaciological reconstruction based on mapping from satellite imagery and digital elevation models (DEMs). Glacial geomorphology is mapped and late-glacial ice dynamics are reconstructed for two mountainous regions of the Northern Hemisphere: the central parts of the Cordillera in western Canada and central Transbaikalia in Siberia, Russia.

2. Motivation

Regions outside the core areas of the Fennoscandian, Laurentide and British ice sheets (FIS, LIS and BIS respectively) frequently display a glacial landform record created under warm-based subglacial thermal conditions (Kleman et al., 1997; Jansson and Glasser, 2005; Kleman and Glasser, 2007). Reconstructions of successive ice margin positions, examining the ice sheet retreat pattern in these areas, have most commonly been based on the spatial distribution of moraines, eskers and glacial lineations (Punkari, 1982; Kleman et al., 1997; Boulton et al., 2001). The core areas of these ice sheets have, however, mostly been covered by cold-based ice frozen to its substrate (Hindmarsh and Boulton, 1989; Dyke, 1993; Heine and McGlue, 1996; Kleman and Hättestrand, 1999; Jansson and Glasser, 2005; Hubbard et al., 2009), as witnessed by the widespread occurrence of reliet surfaces (Sugden and Watts, 1977; Kleman and Stroeven, 1997; Goodfellow et al., 2008). Cold-based conditions prohibited the formation of subglacial landforms but stimulated the formation of ice-marginal meltwater features (Sugden and John, 1976; Dyke, 1993). Meltwater features were successfully incorporated in local- and regional-scale detailed reconstructions of ice retreat (e.g., Borgström, 1989; Johansson, 1995; Jansson, 2003; Stokes and Clark, 2004). The potential for employing meltwater landforms in ice retreat reconstructions at ice sheet scales, and thus including both formerly cold-based and warm-based areas, has been described by Kleman et al. (2006). However, only few examples exist where this has been fully achieved (e.g., Clark et al., in press). To allow for the successful use of meltwater features in ice retreat reconstructions on ice sheet sector to ice sheet scales, mapping procedures and an evaluation of potential data...
sources were yet to be explored. Mapping of glacial geomorphology from remotely sensed and digital elevation data has previously been addressed in methodological studies by for example Clark (1997) and Smith et al. (2006), but meltwater features were not considered in these studies. Therefore, a methodological study focusing on the mapping of meltwater features from remotely sensed data represents the necessary foundation of this PhD project (Paper I).

The aim of the methods study was to evaluate the results of a mapping of all meltwater landforms that are of importance for ice retreat reconstructions from remotely sensed data and DEMs against field control. However, fossil glacial lake shorelines were not identified in the remote sensing imagery of the three study areas (Paper I), even though, for example, the study area in northern Finland is known to host glacial lake shorelines (Johansson, 1995; Helmens et al., 2009). Furthermore, no delta morphology was distinguished in the data although one was identified in the Scotland field site (Paper I). Glacial lakes constitute an important part of the meltwater system and glacial lake landforms are important features in ice marginal retreat reconstructions as these features form both in the cold- and warm-based subglacial environment (Borgström, 1989; Jansson, 2003). Therefore, a mapping survey was required to test the potential of remotely sensed data and DEMs to map these features. The region of central Transbaikalia in central Siberia, Russia, was selected for this mapping survey. This area has thus far received scanty interest in international literature. Fossil shorelines and deltas identified in this area document the former existence of a large ice-dammed lake in the catchment of the River Vitim (Krivoronogov and Takahara, 2003; Enikeev, 2009; Paper II; Paper IV). Moreover, the region of Transbaikalia displays sharp contrasts between non-glacial landscapes and glacially modified terrains of different character. The mapping survey of central Transbaikalia (Paper II) comprises an inventory of the glacial geomorphology and a reconstruction of former glacial lakes. This survey has also served as a basis for a GIS analysis of Glacial Lake Vitim and its drainage (Paper IV).

The retreat patterns of the FIS, LIS and BIS are relatively well known (Dyke and Prest, 1987; Kleman et al., 1997; Boulton et al., 2001; Dyke et al., 2003; Clark et al., in press). In contrast, the demise of the Cordilleran Ice Sheet (CIS), the westerly neighbour of the LIS, is still poorly understood. Reconstructions of ice marginal retreat patterns of the CIS in the Canadian Cordillera are complicated by the complex topography and hindered by a sparseness of recessional moraines. The abundant occurrence of meltwater features in central British Columbia (e.g., Tipper, 1971a), on the other hand, would form the prerequisite for conducting a successful ice sheet retreat reconstruction on a regional scale. Hence, regional CIS retreat reconstructions based on meltwater landforms were accomplished in central and northern British Columbia and in southern Yukon Territory (Papers III, V and VI).

3. Objectives

The objectives of this PhD project are to (i) evaluate data sources for mapping of glacial meltwater landforms, (ii) explore the possibilities to include glacial meltwater features in regional-scale geomorphological mapping and, (iii) utilize

Figure 1. Location of the study areas.
landforms created by glacial meltwater in regional-scale reconstructions of ice sheet retreat and dynamics. Study areas (Fig. 1) were selected based on the motivation given above. To achieve the objectives, the following targets (see also Fig. 2) were developed:

Stage 1
- Evaluate available digital data for regional-scale mapping of meltwater features.
- Test the procedure of direct digitising from satellite imagery in a GIS environment against the traditional interpretation derived from stereoscopically viewed aerial photographs.

Stage 2
- Create a glacial geological map for the region of central Transbaikalia.
- Map meltwater landforms in British Columbia and southern Yukon Territory.

Stage 3
- Reconstruct the ice retreat pattern of the CIS in central British Columbia and southern Yukon Territory.

Stage 4
- Support the ice retreat reconstruction in central British Columbia with absolute dating of selected meltwater features (in progress; outside the scope of the thesis).

Subsequently, the mapping study covering the area of central Transbaikalia (Paper II) developed into an independent project concerning the drainage of Glacial Lake Vitim (Paper IV) and the glacial history of the area (in progress; outside the scope of the thesis).

4. METHODS

4.1. Landforms of the meltwater system

Glacial meltwater is produced by the melting of glacial ice. Even though melting occurs in the ablation areas of glaciers and ice sheets during the advance stage, the majority of meltwater landforms in the landscape originate from the retreat stage (Dyke, 1993; Kleman and Borgström, 1996) because meltwater features, once formed, are not subsequently altered by glacial processes.

Glacial meltwater landforms, whether erosional, such as meltwater channels or fossil shorelines of glacial lakes, or depositional, such as eskers, perched deltas, outwash fans or plains, or glaciolacustrine sediment fills, constitute a deglacial envelope (e.g., Kleman et al., 2006), thus defining the style and direction of ice retreat at local and regional scales (Sugden and John, 1976, Kleman and Borgström, 1996). Meltwater landforms complement other indicators of deglacial ice dynamics such as moraines or glacial lineations.
and they represent the main record of deglaciation, especially where ice remained cold-based and where other traces are absent (Kleman and Borgström 1996; Kleman et al., 2006). An inversion model is applied to reconstruct the configuration of successive glacier- or ice sheet margins (Kleman and Borgström, 1996; Kleman et al., 2006; Greenwood et al., 2007). In this process, the landform record is classified into groups that form “fans” or “swarms” with glaciologically plausible patterns (Kleman and Borgström 1996, Kleman et al., 2006). The principle of superposition (e.g., Clark, 1997), where landforms of one swarm overprint landforms of another swarm, defines relative age relationships (Kleman and Borgström 1996, Kleman et al., 2006) and allows for a relative age-stacking of individual swarms (e.g., Kleman et al., 1997). Hence, landforms represented in the mapped geomorphological record do not necessarily define a single continuous evolution of the examined glacier or ice sheet. For example, cold-based subglacial thermal regimes facilitate the preservation of previously-formed glacial landforms before a subsequent overprinting of deglaciation landforms (Kleman, 1994).

4.2. Data and software

Satellite imagery and digital elevation models (Table 1, Paper I) were acquired for the study areas of Paper I. Two of the three test areas were also mapped in aerial photographs. The mapping surveys presented in papers II and III were based solely on freely available data. The glacial map of central Transbaikalia (Paper II) was mapped with the use of the Shuttle Radar Topographic Mission (SRTM, Jarvis et al., 2008) DEM with 90 m spatial resolution and Landsat 7 ETM+ satellite imagery (USGS, 2010). The Transbaikalia study area was also mapped from Google Maps that display slope images from SRTM data combined with medium- and high-resolution satellite imagery.

Data of higher spatial resolution were available for the Canadian study area. This included the Canadian Digital Elevation Data (2009) with a spatial resolution of c. 20 m (0.75 arcseconds) and SPOT 4 and SPOT 5 satellite images. High resolution satellite imagery was available for most parts of the Canadian study area through Google Maps/Google Earth.

Mapping was performed at multiple scales in ESRI® ArcMap 9.2. Where applicable, digitizing was performed directly in Google Maps. Such mapping results were subsequently imported into Google Earth, saved as kml-files, and converted to the shp-files for use in ArcGIS using the DNR Garmin (2009) application.

5. Presentation of papers

5.1. Paper I


Satellite imagery and digital elevation data suitable for mapping the glacial geomorphology at a regional scale, including the meltwater system, were collected for and tested at three different study sites in Scotland, Finland and Sweden. The data set also included aerial photographs (for two areas) and one high-resolution DEM. The objectives were to evaluate the potential of these different data sets for the mapping glacial meltwater landforms and to offer a recommendation for their use in large scale mapping efforts.

Most available scales of aerial photographs allow for detailed mapping. However, the transformation of analogue mapping in aerial photographs to the digital format is a relatively time-consuming process that introduces inaccuracies in the final results. The introduced inaccuracies could be minimized by using digital aerial photographs. The use of digital aerial photographs will, however, still be relatively more time-consuming than the use of satellite imagery in regional mapping efforts. High-resolution DEMs alone or in combination with medium-resolution (15 m) satellite imagery are suitable data sources for the mapping of meltwater landforms. The potential for the mapping of meltwater features was identified in the SPOT and ASTER imageries. When mapping meltwater landforms from digital data, spatial resolution of the data is the most important attribute influencing the quality of the results while radiometric resolution is of additional significance in satellite imagery. Our results show that mapping from digital data of medium resolution is likely to show a loss of detail when compared to mapping from aerial photographs but that overall patterns might be captured.

5.2. Paper II


This study presents the first glacial geomorphological map covering the region of central Transbaikalia, a mountainous area east of Lake Baikal in Siberia, Russia, and adds knowledge about the glacial geomorphology of this remote area. The extent of glacially modified terrain, glacial lake landforms, moraines, glacial lineations and meltwater channels were mapped in SRTM data, Landsat 7 ETM+ satellite imagery and Google Maps. The distribution of glacial lake landforms allows for the reconstruction of several glacial lakes of which the one formed in the catchment of the River Vitim was the most prominent. We suggest that the mapped glacial record most probably represents the product of several glacial stages. These glacial stages are represented by multiple moraines preserved in some valleys and by the existence of glacially-modified terrain in places extending beyond the outermost moraines.

5.3. Paper III

This mapping survey focuses on glacial meltwater landforms in the area of central British Columbia. Ice-marginal meltwater channels, eskers and deltas were mapped from satellite imagery and digital elevation data. The results show a consistent spatial pattern of high-elevated ice-marginal channels in the Skeena and Omineca mountains, in higher areas of the Interior Plateau and in the marginal ranges west of the plateau, and to a lesser extent also in the Rocky Mountains. Eskers mapped in the study area can be classified into three main groups: (i) small eskers with random directions, (ii) mainly single-ridged, medium-sized eskers trending in directions consistent with the direction of regional ice flow indicators (e.g., drumlins), and (iii) large multiple-ridged esker accumulations, confined to depressions and valleys on the Interior Plateau, that differ in direction from regional ice flow indicators. Spatial analysis of the glacial meltwater landforms allows for the interpretation of the late glacial history of, and reconstruction of CIS retreat in, central British Columbia.

5.4. Paper IV


This paper builds on Paper II and includes geomorphological evidence for the existence of a large glacial lake dammed on the River Vitim in central Transbaikalia, Siberia, and for its catastrophic drainage. A prominent canyon perched on the slope of the River Vitim valley in the area of the postulated ice dam is interpreted as being formed by fluvial erosion at the time of the breaching of the ice dam. Possible environmental impacts of the postulated giant flood into the Lena River catchment are discussed and the occurrence of a freshwater spike recorded in a marine sediment core drawn near the Lena River mouth in the Arctic Ocean is noted and could potentially pinpoint the timing of this event to ~13 cal ka BP.

5.5. Paper V


In this paper, the late glacial history of the CIS in central British Columbia is reconstructed on the basis of a regional-scale mapping survey of glacial meltwater landforms (Paper III). A significant reconfiguration of the ice divide must have occurred in the period between the local LGM and the time when the highest ice-marginal meltwater channels were formed. This is inferred from a consistent spatial pattern of high-elevated ice-marginal meltwater channels that indicate the ice divide to have been located above the Coast Mountains during the late glacial. This evidence locally conflicts with suggested LGM ice divide positions further east. No evidence is found for the existence of large accumulation areas in the east at the time of deglaciation. At the time when ice-marginal meltwater channels were formed close to the Coast Mountains accumulation areas, the eastern margin of the CIS retreated to the west. During the early phase of this retreat, glacial lakes were dammed by the ice margin in valleys of the Rocky Mountains draining west. Subsequently, a major glacial lake formed along the Fraser River, and drained once the ice margin retreated further to the west and southwest towards the Coast Mountains. An active frontal retreat is inferred to have occurred in the valleys of the Omineca and Skeena mountains during the final stages of deglaciation. At the same time, large eskers formed in the main valleys of the Interior Plateau at oblique angles to the direction of last active ice flow in the area. This is interpreted to indicate the presence of inactive and stagnating ice remnants over the Interior Plateau during final deglaciation.

5.6. Paper VI

Margold, M., Jansson, K.N., Kleman, J., Stroeven, A.P. (manuscript): Late-glacial ice dynamics of the Cordilleran Ice Sheet in northern British Columbia and southern Yukon Territory: retreat pattern of the Liard Lobe reconstructed from the glacial landform record.

This paper contains a first reconstruction of the ice retreat pattern of the Liard Lobe in the northeastern sector of the CIS across the boundaries between British Columbia, the Yukon Territory and the Northwest Territories. At the local LGM, the Liard Lobe extended from ice divide areas in the Skeena, Cassiar, Pelly and Selwyn Mountains across the Liard Lowland into the Hyland Highland (Fig. 3) with a consistent northeast oriented ice slope that stretched over 350 km. The retreat of the Liard Lobe is indicated by large easterly-oriented meltwater channels in the Hyland Highland formed by the drainage of glacial lakes dammed by the retreating ice margin. A southwestern direction of the ice retreat is also indicated by sets of ice-marginal meltwater channels in higher areas of the Hyland Highland and at the southeastern foot of the Selwyn Mountains. Two large dendritic esker systems running across the Liard Lowland indicate a consistent ice slope during the deglaciation. Esker deltas, outwash fans, ice-contact sediments and ice-marginal meltwater channels are found locally at the foot of the Cassiar Mountains and further up-valley in the Cassiar Mountains indicating two positions of the retreating ice front late during deglaciation.

6. Discussion and summary

6.1. Late glacial history of the Cordilleran Ice Sheet

6.1.1. LGM configuration

During the local LGM, the CIS covered all of the western, mountainous part of Canada except for areas in the western and northern Yukon Territory and ice-free areas isolated between the CIS and the LIS in the Northwest Territories.
Columbia Mountains (Fig. 3; Ryder et al., 1991; Clague and Ward, 2011). An ice saddle at approximately 2000; Clague and Ward, 2011). To the south of the Skeena ice dome was connected by a major ice divide that stretched from the Skeena Mountains in northern British Columbia during the last glacial period (Fraser/McConnell glaciation, OIS 2; Fulton, 1991). It is suggested that an ice dome formed above the Skeena Mountains in northern British Columbia during the last glacial period (Fraser/McConnell glaciation, OIS 2; Stumpf et al., 2000). In the north, the Skeena ice dome was connected by a major ice divide with an east-west oriented ice divide that stretched from the Mackenzie Mountains to the northern Coast Mountains and the Saint Elias Mountains (Fig. 3; Jackson et al., 1991; Stumpf et al., 2000). In the north, the Liard Lobe retreated from the east towards the LGM position of the ice divide in the Cassiar Mountains. The post LGM development in place of the Skeena ice dome is not known as well as the ice configuration in the northern Coast Mountains.

Even though the main LGM outlines of the CIS have been established, our knowledge about the ice sheet at the peak of the last glacial period must be regarded as low. The maximum extent was reached in different sectors of the ice sheet at different times; earlier in the north and later in the south (Clague et al., 1980; Porter and Swanson, 1998; Stroeven et al., 2010). Regardless of the accepted existence of the Skeena ice dome, the style of glaciation during the local LGM still remains an open question and questions regarding the ice thicknesses, main ice discharge routes and the degree of dependence on the underlying topography still need to be answered (Bednarski and Smith, 2007; Kleman et al., 2010; Stroeven et al., 2010).

6.1.2. Ice retreat pattern

Late glacial ice dynamics have been examined for two regions of the CIS using the meltwater landform record. Ice retreat patterns at a regional scale were interpreted using macro-scale ice-flow indicators such as glacial lineations and the “deglacial envelope” of meltwater landforms (Kleman and Borgström, 1996; Kleman et al., 2006). Locally, ice retreat patterns were reconstructed in greater detail, particularly where the record of meltwater landforms was extensive (Paper V, Figs. 4, 5 and 7, Paper VI, Fig. 5).

In north-central British Columbia an ice divide shift towards the Coast Mountains, postdating the local LGM, is reconstructed from a consistent pattern of northeast trending ice-marginal meltwater channels that occur in high elevations in the western parts of the Interior Plateau and in the eastern marginal ranges of the Coast Mountains. These northeast
trending channels conflict with the suggested LGM position of the ice divide in north-central British Columbia established from the pattern of ice-flow indicators (Stumpf et al., 2000; McCuaig and Roberts, 2002). The mapped pattern of ice-marginal meltwater channels implies the ice divide to have been located above or close to the Coast Mountains when the channels were formed. Therefore, the ice divide must have changed position before the summit areas of the eastern marginal ranges of the Coast Mountains protruded through the ice surface.

A detachment of the eastern CIS margin from the western slopes of the Rocky Mountains is documented by an abundance of meltwater landforms in the north-central part of the Interior Plateau. The situation is more difficult to establish farther south for this period, because the record of glacial meltwater landforms is sparse in the Columbia Mountains and on their western slopes. However, high-elevation ice-marginal channels in the south-central part of the Interior Plateau indicate an easterly sloping ice surface of Coast Mountains-sourced ice. No clear evidence is available for substantial ice dispersal centres remaining in the Columbia Mountains at this time.

Similarly to the ice retreat pattern in central British Columbia, also the region of northern British Columbia, the southern Yukon Territory and the southwestern extremity of the Northwest Territories exhibits a dominance of a westerly-sourced ice after the local LGM with an ice marginal retreat towards the west during late glacial time. Active ice retreat towards a minor accumulation area in the Selwyn Mountains has been reconstructed by Dyke (1990). At the regional scale, it appears that the role of accumulation areas in the eastern mountain ranges such as the Mackenzie Mountains and the Rocky Mountains diminished strongly after the LGM. This was possibly a consequence of a strong west-east precipitation gradient, which caused the eastern portions of the CIS to be starved of precipitation. Together with the warming climate, it then caused the eastern CIS margin to retreat towards the west. The mountain ranges that were vacated by the CIS might still have supported mountain glaciers because of a sufficiently low equilibrium line altitude (Smith, 2003, 2004; Lakeman et al., 2008).

The study areas of papers V (central British Columbia) and VI (areas covered by the Liard Lobe) are separated by a large region where the interior area between the Coast

**Figure 4.** Palaeoglaciology of north-central Eurasia. Schematic outlines of the successively less extensive Barents-Kara Ice Sheet in the Middle and Late Pleistocene are indicated in dark blue after Svendsen et al. (2004) with glacial lakes dammed by the ice sheet indicated for 90 ka extent of the ice sheet (after Mangerud et al., 2004). The extents and chronology of glaciations in the mountains of north-central Eurasia have not yet been properly reconstructed. Glacially modified terrain mapped in Margold and Jansson (2011, black rectangle) for the area of central Transbaikalia is indicated in pink, Glacial Lake Vitim in bright blue. Ice cap identified by Grosswald in the headwaters of the Yenisei River (1965, in Komatsu et al., 2007) is indicated schematically by a dashed ellipse. Extensive ice cover developed at some point also in the Altai Mountains (Lehmkuhl et al., 2004) and the Verkhoyansk Mountains (Stauch and Guaitieri, 2008; Stauch and Lehmkuhl, 2010).
Mountains and the Rocky Mountains (sensu Fulton, 1991) is occupied by mountain ranges (Fig. 3). As stated above, a prominent ice dome existed over the Skeena Mountains during the LGM time in this area (Fig. 3; Ryder and Maynard, 1991; Stumpf et al., 2000; McCuaig and Roberts, 2002). The highest ice-marginal meltwater channels in the Skeena and Omineca Mountains provide evidence for the existence of a uniform ice surface east of the LGM ice divide. Ice-marginal meltwater channels at gradually decreasing elevations on the mountain slopes then record a lowering of this uniform ice slope and a retreat of glacier lobes through the valleys towards the areas of the final ice divide. However, the scarcity of meltwater features in the areas to the west of the LGM ice divide precludes reconstructing the ice retreat pattern in this part of the CIS. The reconstruction of ice-flow directions (Stumpf et al., 2000) in the mountainous area to the northwest of the Interior Plateau suggests that once the Skeena ice dome vanished, ice dispersal centres from the CIS build-up stage were re-established in both the Coast Mountains and in the Skeena Mountains. Retreat of ice lobes from the coast to the northeast has been described by Clague (1985) for the Skeena River area. Similarly, the pronounced glacial streamlining of the terrain in the Nass Depression further to the north from the Skeena River area and the lack of ice stagnation landforms here has been interpreted as a possible indication of an active ice retreat towards the accumulation area (Ryder and Maynard, 1991). The exact configuration of the retreating ice sheet in this wider region still remains unclear. Either local ice dispersal centres were re-established in the highest mountains such as described by Stumpf et al. (2000) or the Skeena ice dome maintained its dominance throughout the deglaciation with the last remnants of the diminishing ice sheet melting in the position of the LGM ice dome.

6.2. Glacial lake dynamics in central Transbaikalia

Glacial geomorphology has been mapped and glacial lakes have been reconstructed for the area of central Transbaikalia in Siberia, Russia. The most prominent of these glacial lakes formed in the upper catchment of the River Vitim when the valley was blocked by glaciers descending from the Kodar Mountains (Fig. 4). The landform record, including fossil shorelines and perched deltas, allowed for reconstructing the maximum area and volume of Glacial Lake Vitim (23,500 km², ~3000 km³). Its maximum stage was controlled by an ice dam. Ice-marginal meltwater channels at gradually decreasing elevations on the mountain slopes then record a lowering of this uniform ice slope and a retreat of glacier lobes through the valleys towards the areas of the final ice divide. However, the scarcity of meltwater features in the areas to the west of the LGM ice divide precludes reconstructing the ice retreat pattern in this part of the CIS. The reconstruction of ice-flow directions (Stumpf et al., 2000) in the mountainous area to the northwest of the Interior Plateau suggests that once the Skeena ice dome vanished, ice dispersal centres from the CIS build-up stage were re-established in both the Coast Mountains and in the Skeena Mountains. Retreat of ice lobes from the coast to the northeast has been described by Clague (1985) for the Skeena River area. Similarly, the pronounced glacial streamlining of the terrain in the Nass Depression further to the north from the Skeena River area and the lack of ice stagnation landforms here has been interpreted as a possible indication of an active ice retreat towards the accumulation area (Ryder and Maynard, 1991). The exact configuration of the retreating ice sheet in this wider region still remains unclear. Either local ice dispersal centres were re-established in the highest mountains such as described by Stumpf et al. (2000) or the Skeena ice dome maintained its dominance throughout the deglaciation with the last remnants of the diminishing ice sheet melting in the position of the LGM ice dome.

7. Future perspectives

7.1. Late glacial history of the Cordilleran Ice Sheet

Connecting the deglaciation histories of the areas of papers V and VI and reconstructing the fate of the Skeena ice dome after the LGM and thus establishing a CIS ice retreat pattern at the full ice sheet scale remains a task for future research efforts. The reconstruction of ice sheet retreat patterns and the thus derived relative deglaciation history need to be supported by an absolute chronology of deglaciation. To contribute to this, samples for terrestrial cosmogenic nuclide (TCN) dating were collected at two sites with high-elevated ice-marginal meltwater channels in central British Columbia (Fig. 5). These samples will help to establish when these summit areas bordering the Interior Plateau were deglaciated. Future, more extensive dating efforts should provide more information for the time correlation of ice retreat in different sectors of the CIS. Together with the framework provided by ice sheet-scale reconstructions of CIS retreat and forthcoming TCN dating, local ice retreat histories will have the potential...
Retreat pattern and dynamics of glaciers and ice sheets

7.2. Glacial history of central Transbaikalia, Siberia

The Pleistocene glacial history of the mountains of central Siberia has not received much attention and remains largely unknown for the international scientific community. Glacial geomorphological mapping of the mountainous region to the east of Lake Baikal revealed U-shape valleys and glacially-streamlined terrain away from the core areas with well-developed alpine relief (Margold and Jansson, 2011). Northwest of the Kodar Mountains (the highest mountain range of the region reaching almost 3000 m above sea level), the valley of the River Vitim has been interpreted as glacially modified along a distance of more than 200 km from the water divide (Margold and Jansson, 2011). The observation of glacial polish and associated striae at outcrops in the town of Bodaybo (Figs. 4 and 6) and the indisputably glacial shape of the Vitim River valley (Fig. 6) support the notion of an extensive glaciation of the region.

Such traces of extensive glaciers motivate attempts to establish the spatial pattern and chronology of former glaciation. A first step towards this objective is the glacial geomorphology map of Margold and Jansson (2011) that displays multiple generations of moraines in most of the mountain ranges. Future studied, however, would need to confirm the furthermost glacial limits by detailed remote sensing studies and field surveying, and establish relative and absolute chronologies of the moraines using TCN dating of boulders on moraine crests and of exposed glacially eroded surfaces.

Information about the glacial history of the mountains of Transbaikalia would allow for a comparison with established glacial chronologies of other mountain regions of central and northeastern Eurasia (e.g., Stauch and Gualtieri, 2008; Stauch and Lehmkuhl, 2010). A Pleistocene ice cap has previously been identified in the headwaters of the Yenisei River (Fig. 4; Grosswald, 1965 in Komatsu et al., 2007) and extensive glaciations have been described from the Altai Mountains (Lehmkuhl et al., 2004) and the Verkhoyansk Mountains (Stauch and Gualtieri, 2008; Stauch and Lehmkuhl, 2010), even though spatial extents for these glacial events remain to be fully established.

Better knowledge of glacial extents and chronology in central Transbaikalia will also have the potential to help understand how glacial histories of the mountains of central Siberia and the history of the Barents-Kara Ice Sheet relate to each other. The southeastern margin of the Barents-Kara Ice Sheet was during its maximum Pleistocene extent situated some 600 km to the northwest of the mountains of Transbaikalia (Fig. 4). Both the Barents-Kara Ice Sheet and the mountains of Transbaikalia received precipitation from the westerlies. The question, therefore, arises whether maximum glacial extents occurred simultaneously in both regions or whether the Barents-Kara Ice Sheet blocked moisture from reaching farther east and caused cold and arid conditions in the mountains of central Siberia, conditions unfavorable to the development of glaciers. If the former was true, did the extents of glaciation in the mountains of Transbaikalia follow the same trend as the Barents-Kara Ice Sheet, which occupied successively smaller extents during the last glacial period and which did not even reach onto the Eurasian continent east of the Ural Mountains during the LGM (Fig. 4)?

Figure 6. (a) Glacially modified valley of the River Vitim upstream of Bodaybo (see Fig. 4 for location). (b) Glacially striated bedrock in Bodaybo. (c) Detail of the striated surface.
8. Conclusions

- Available digital data for mapping glacial meltwater landforms were evaluated with the conclusion that aerial photographs remain an ultimate source of detailed information. However, satellite imagery with medium to high spatial resolution and especially detailed DEMs have the potential to replace aerial photographs as a data source in regional mapping surveys of the meltwater system.

- The landform record in central Transbaikalia shows the former existence of large glacial lakes in the area. Localized, high-magnitude fluvial erosion in the postulated ice-dam area of Glacial Lake Vitim, the largest of the reconstructed glacial lakes in the area, indicates a possible outburst flood from this lake to the Arctic Ocean.

- Central British Columbia reveals a consistent spatial pattern of ice-marginal meltwater channels at high elevations. Medium-sized eskers consistent with the regional ice flow direction occur on higher ground whereas large esker accumulations often at oblique angles to regional ice flow indicators occur in the main topographic lows.

- CIS ice divide migrated towards the Coast Mountains after the local LGM in central British Columbia. The eastern margin of the CIS was retreating towards the ice divide across the Interior Plateau, damming a glacial lake along the Fraser River. Ice retreat was possibly accompanied by a stagnation of ice lobes on the Interior Plateau.

- The Liard Lobe of the CIS drained ice towards the northeast from ice-divide areas in northern British Columbia and southern Yukon Territory. Active retreat of its ice margin towards the west is reconstructed from the pattern of large meltwater channels in the Hyland Highland and from esker complexes cross-cutting the Liard Lowland. Ice-marginal positions from a late stage of the deglaciation were locally reconstructed at the foot of the Cassiar Mountains and in its easterly trending valleys.

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Retreat pattern and dynamics of glaciers and ice sheets
Retreat pattern and dynamics of glaciers and ice sheets


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